Radiation Shielding for Tomorrow's Spacecraft

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BEAMS: Benchmark Evaluations and Analysis of Materials for Shielding

MMARSS: Multifunctional Materials Analysis of Radiation Shielding for Spacecraft

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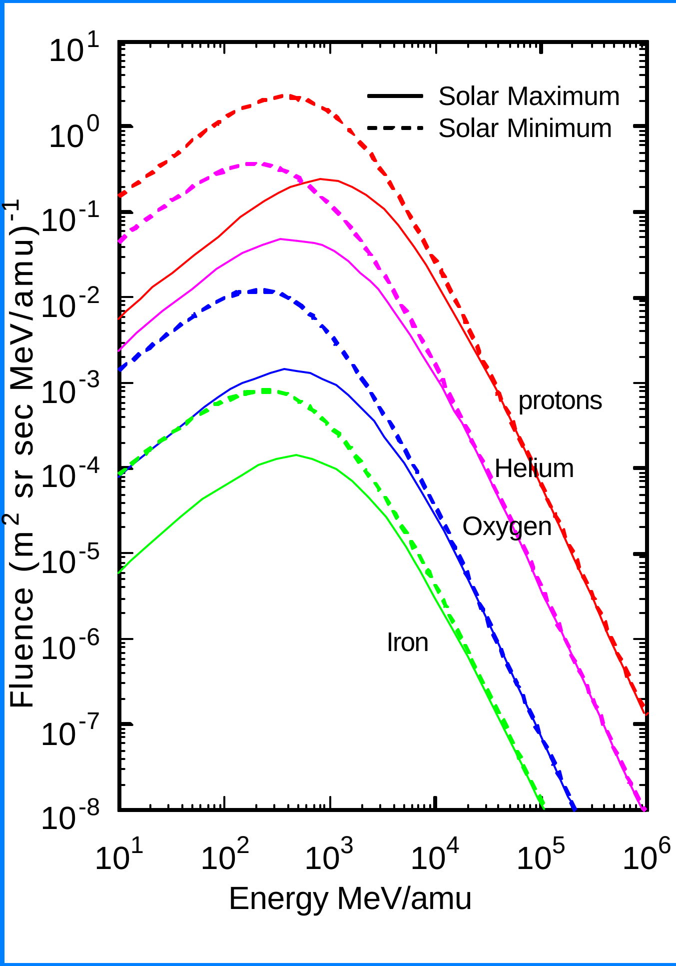
Overview

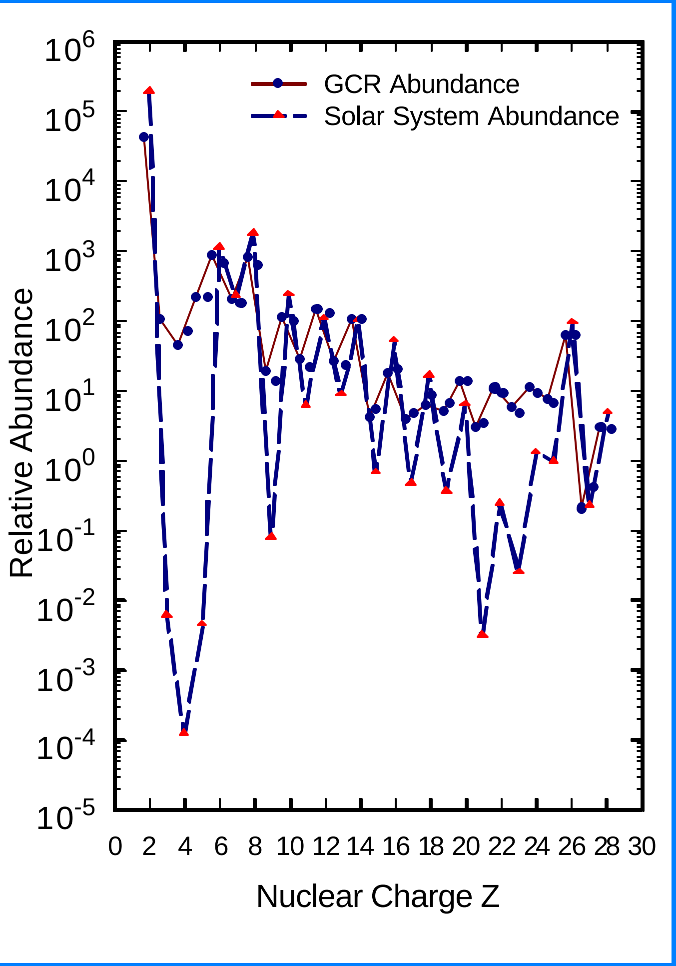
- The Need for Space Radiation Shielding on Piloted Spacecraft
    - Space Radiation Environment
    - Measurements from Mir Orbital Station
    - Mechanisms of Radiation Interaction with Matter
- Initial Results from the BEAMS Project
    - Results from Heavy Ion Exposures
    - Results from Proton and Neutron Exposures
- Overview of MMARSS Project
- Conclusions

Introduction

- Risk to astronaut health and safety from long-duration exposure to ionizing radiation is one of the biggest obstacles to Human Interplanetary Spaceflight and the establishment of a permanent base on the moon.
- Estimate 50 g/cm^2 of Aluminum (18.5 cm or 7.3”) needed to stay below 50 mSv recommended limit for trip to Mars.
- Al shielding can make radiation exposure worse by creating neutrons in nuclear interactions with incident charged particles.
- Secondary neutrons tend to build up with increasing shielding depth, increasing the radiation hazard.

Galactic Cosmic Rays





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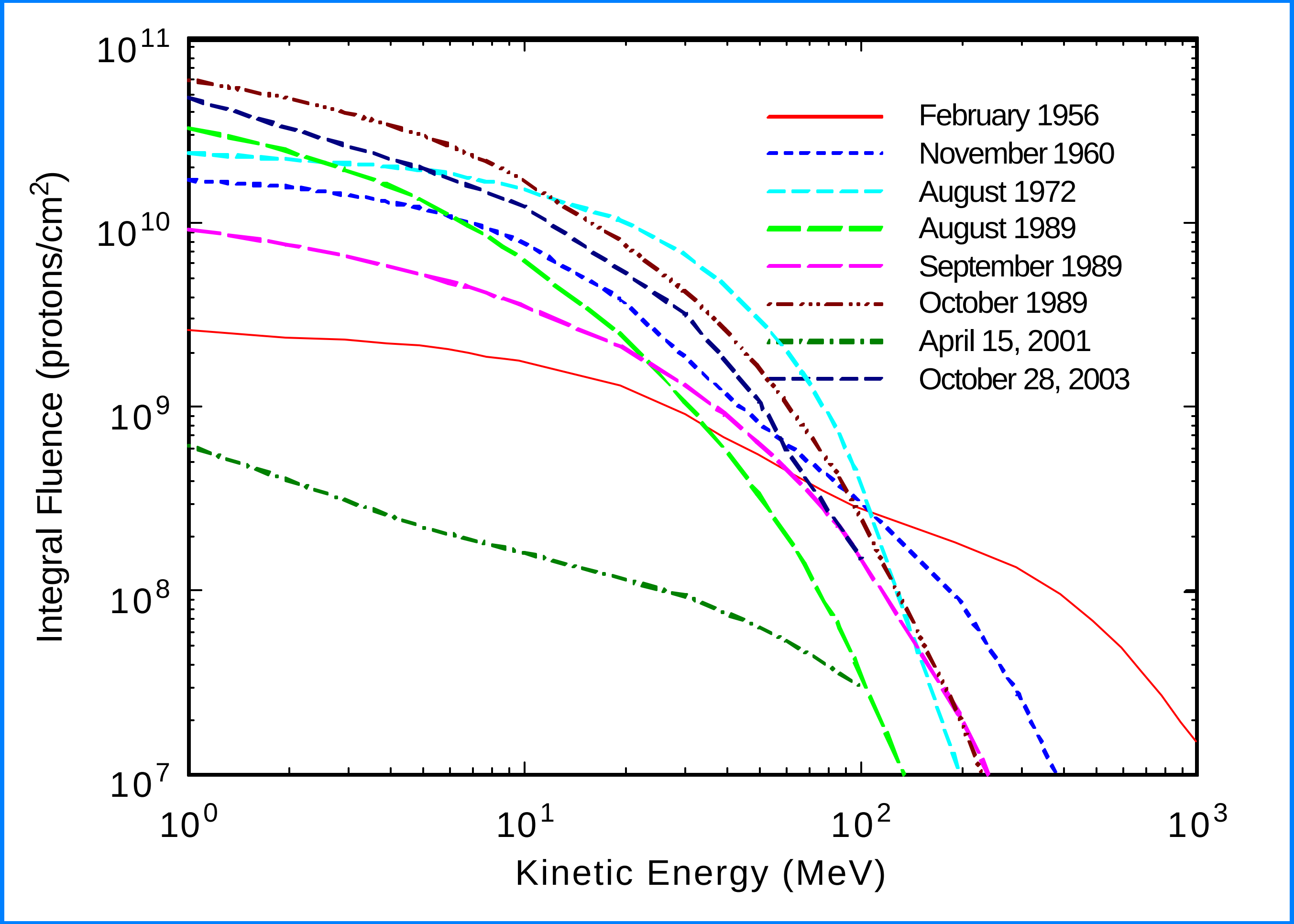
Solar Particle Events



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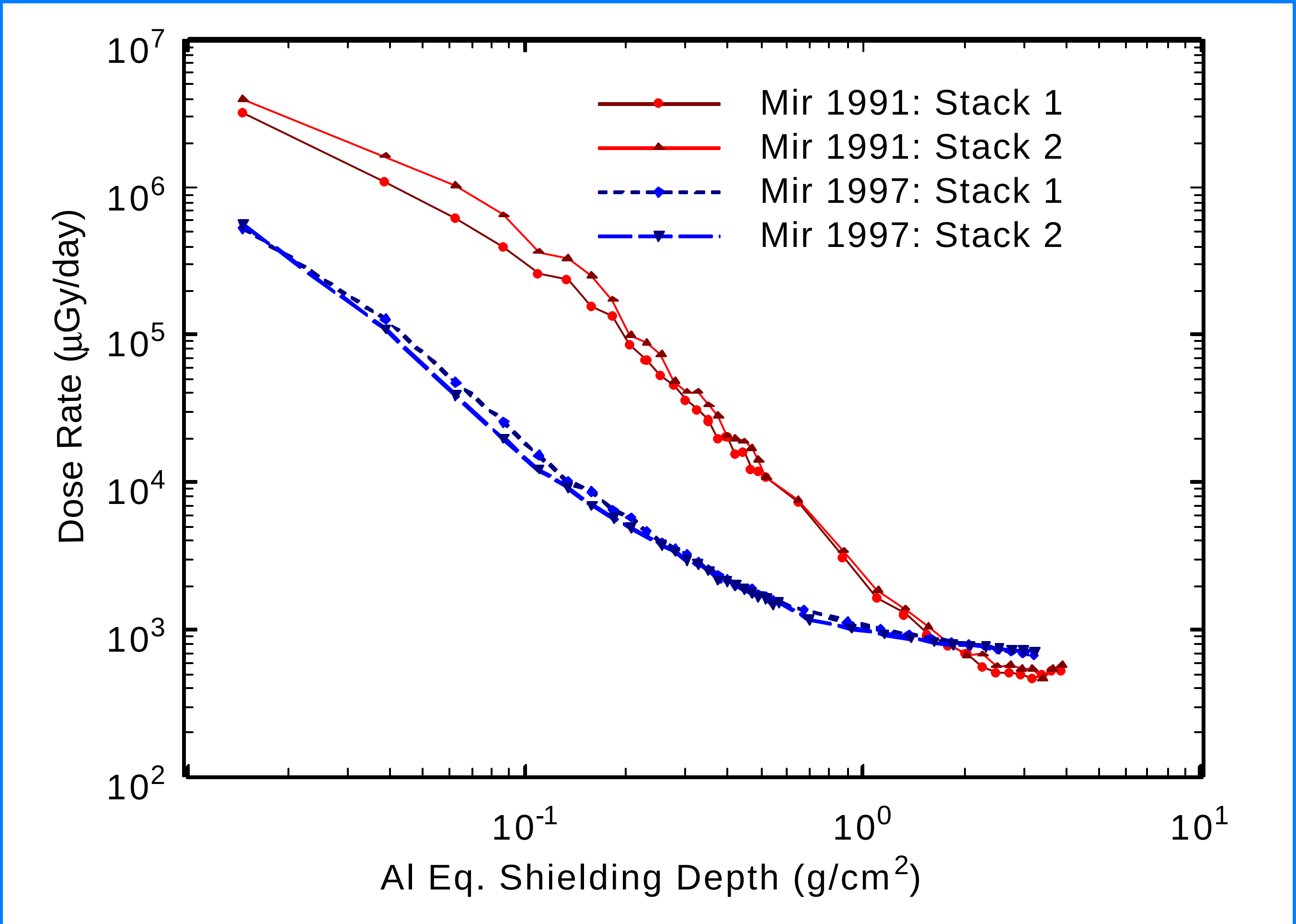
The Space Radiation Shielding Problem

- The Primary Energy Loss Mechanism is Ionization
- In LEO, most of the Flux is Low Energy Protons and Low Energy Electrons that are attenuated within the first g/cm^2
- Energy Spectra of most SPEs are low enough that Spacecraft Shielding will Attenuate most Flux (heavily shielded vault)
- Much of GCR Spectrum is too Energetic to be Effectively Shielding …at least in terms of ionization. Estimate: ~50 g/cm^2
- Nuclear Processes (both Projectile and Target Fragmentation) lead to Production of Secondary Charged Particles and <u>neutrons</u>

Dose Rate as a function of Shielding Depth

Exterior of Mir Orbital Station, measured in ^{7}LiF TLD



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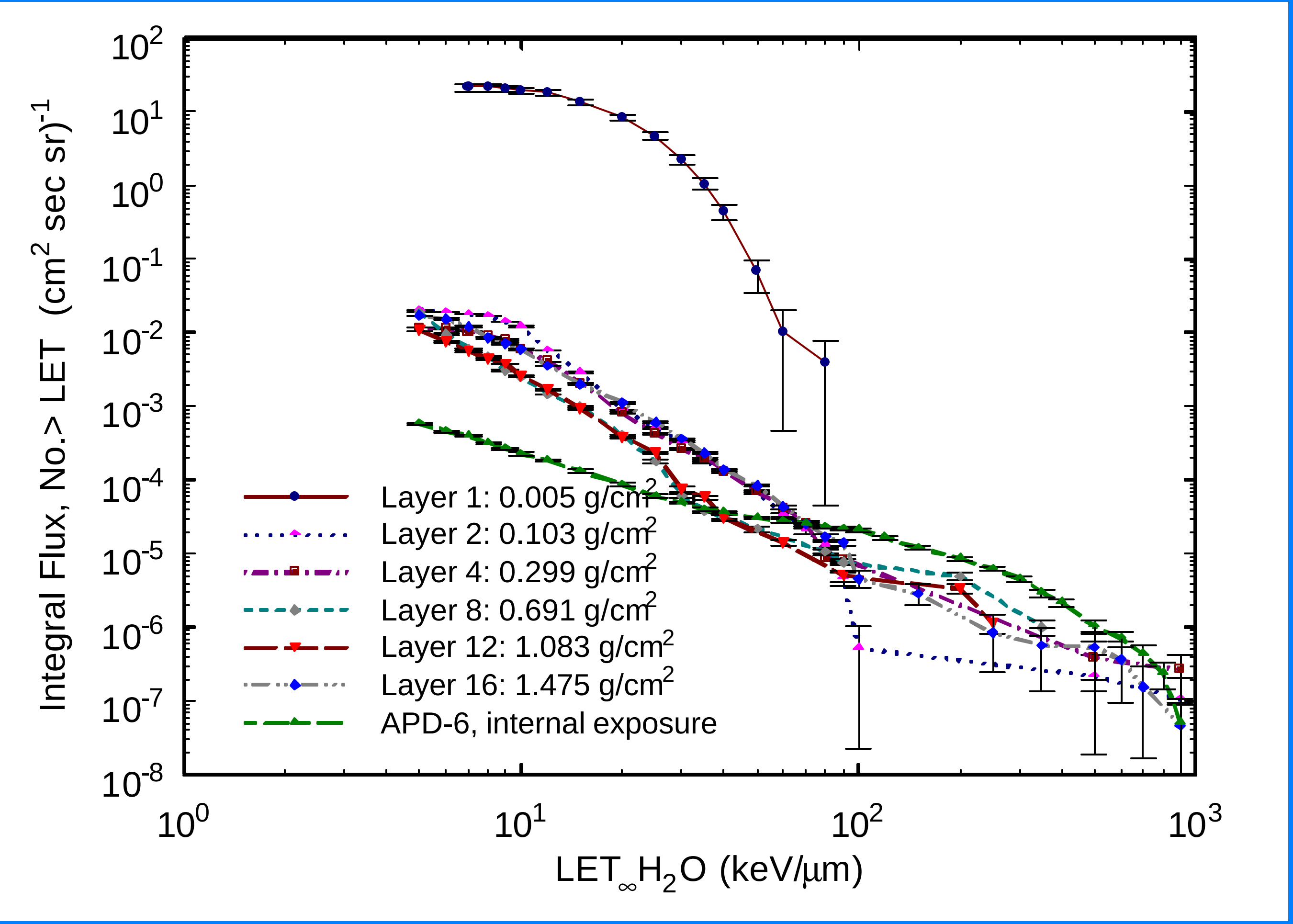
LET Spectra as a function of Shielding Depth

Exterior of Mir Orbital Station, measured in CR-39 PNTD



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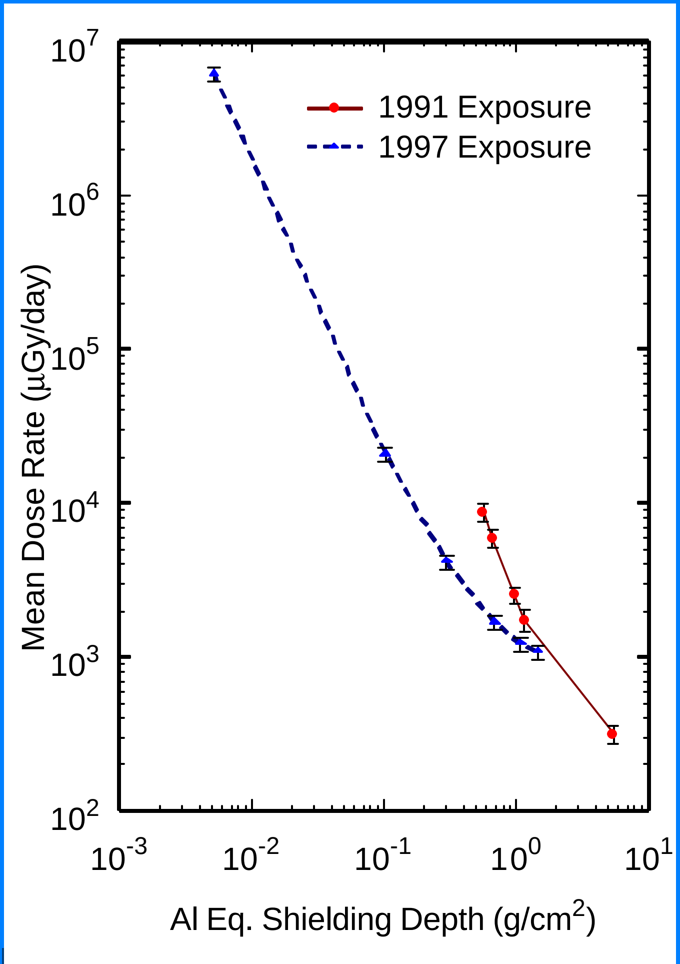
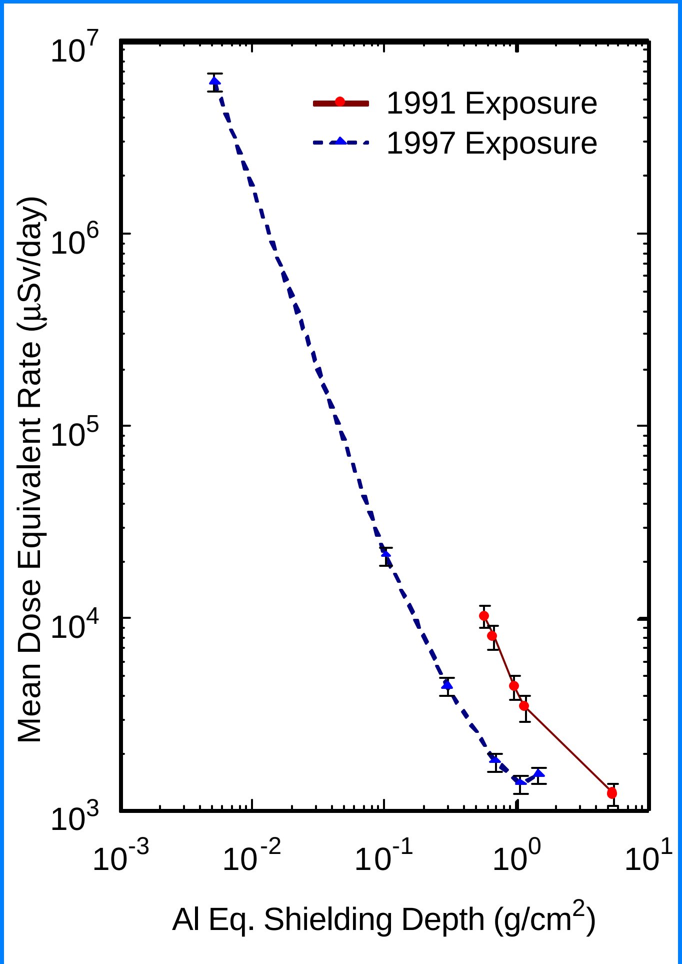
Dose & Dose Equivalent Rates as a function of Shielding Depth

Exterior of Mir Orbital Station, measured in CR-39 PNTD/^{7}LiF TLD





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Materials Properties that Affect Radiation Shielding

Atomic Properties (cross sections)

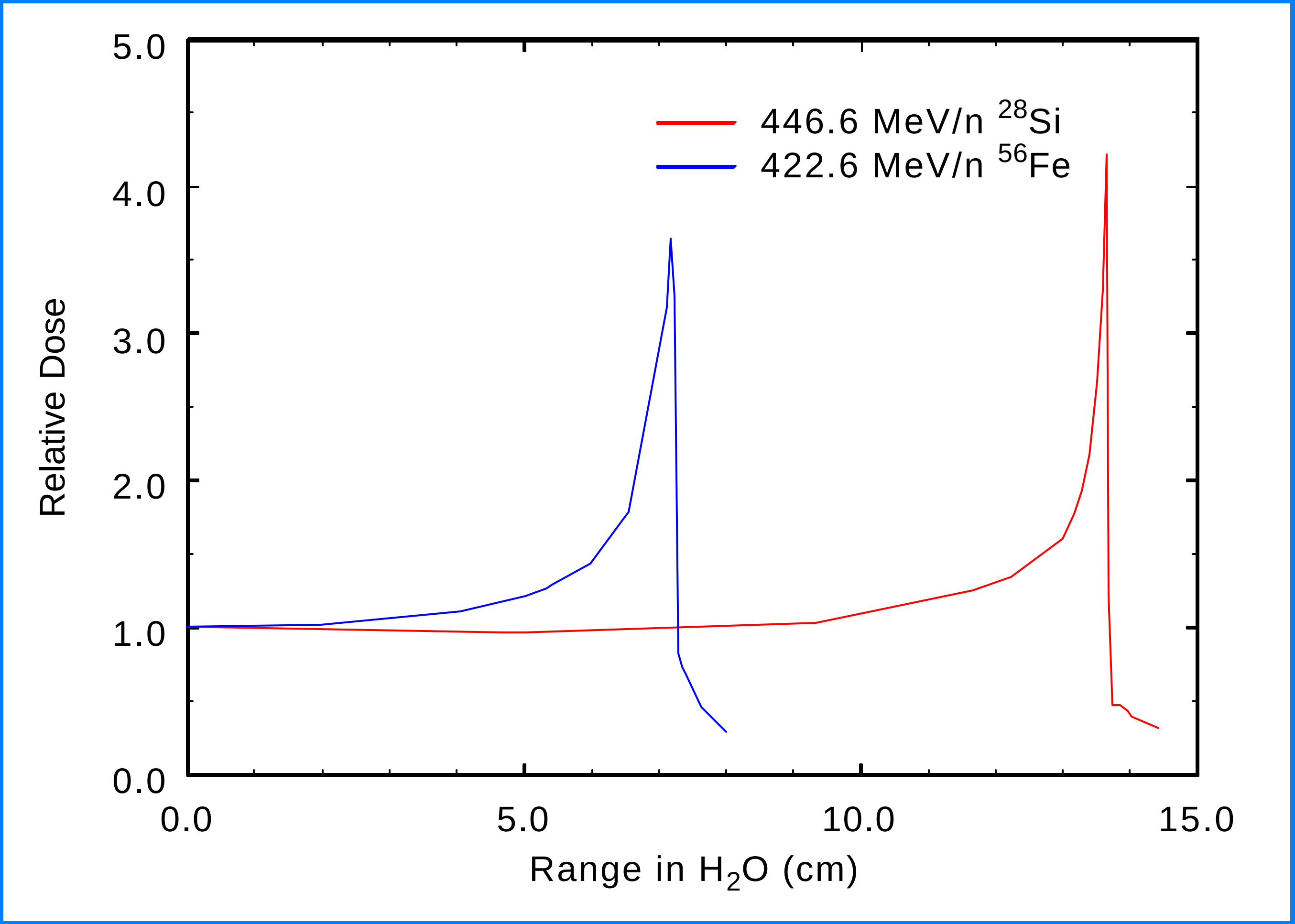
- Number of Electrons Per Unit Volume (high)
- Mean Electronic Excitation Energy (low)
- Tight Binding Corrections of Inner Shell Electrons (low)

Nuclear Properties (cross sections)

- Mean Free Path (short to break up heavy nuclei)
- Composition & Energy Spectrum of Secondaries

Energy Loss Through Ionization

Bragg Curves Measured at HIMAC



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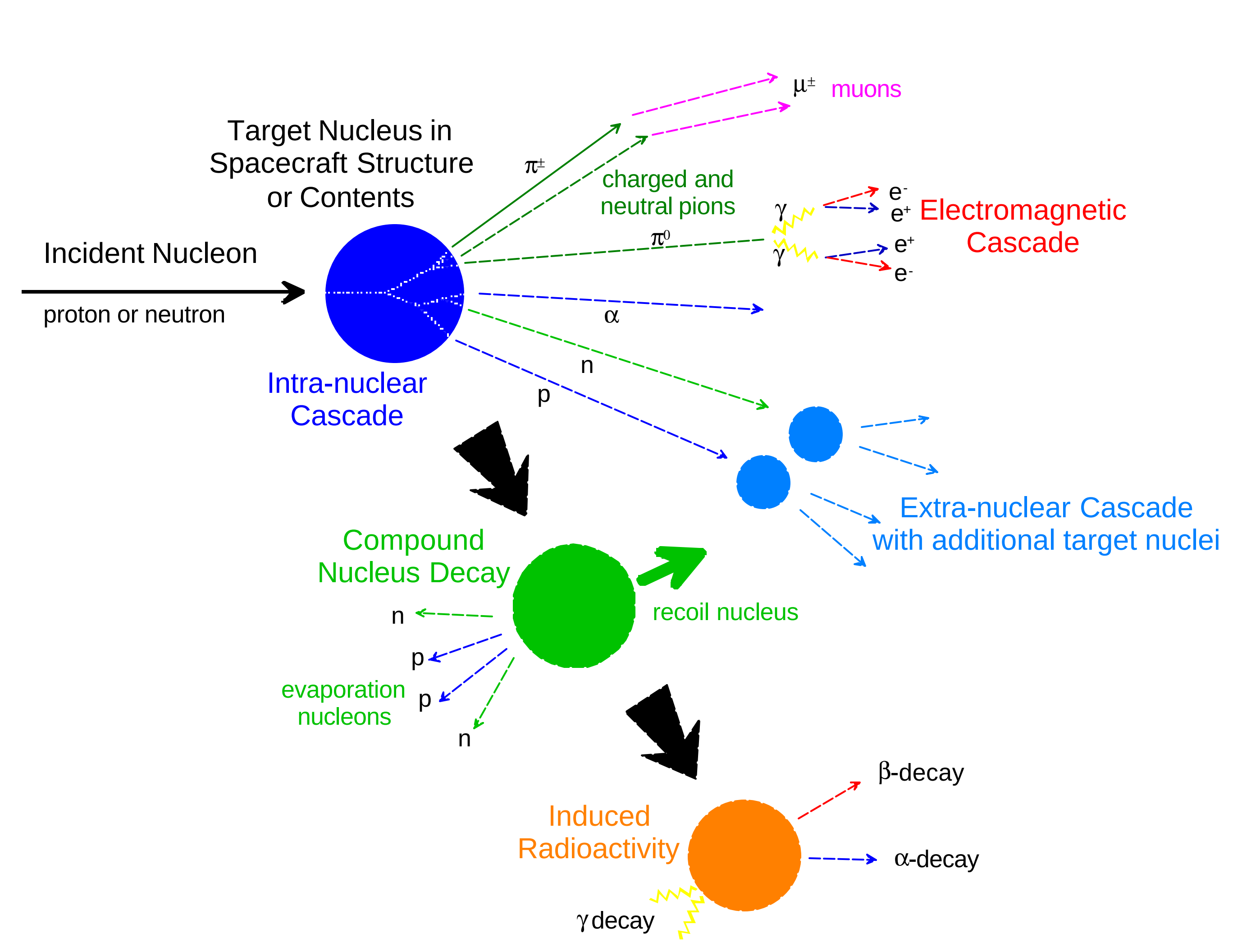
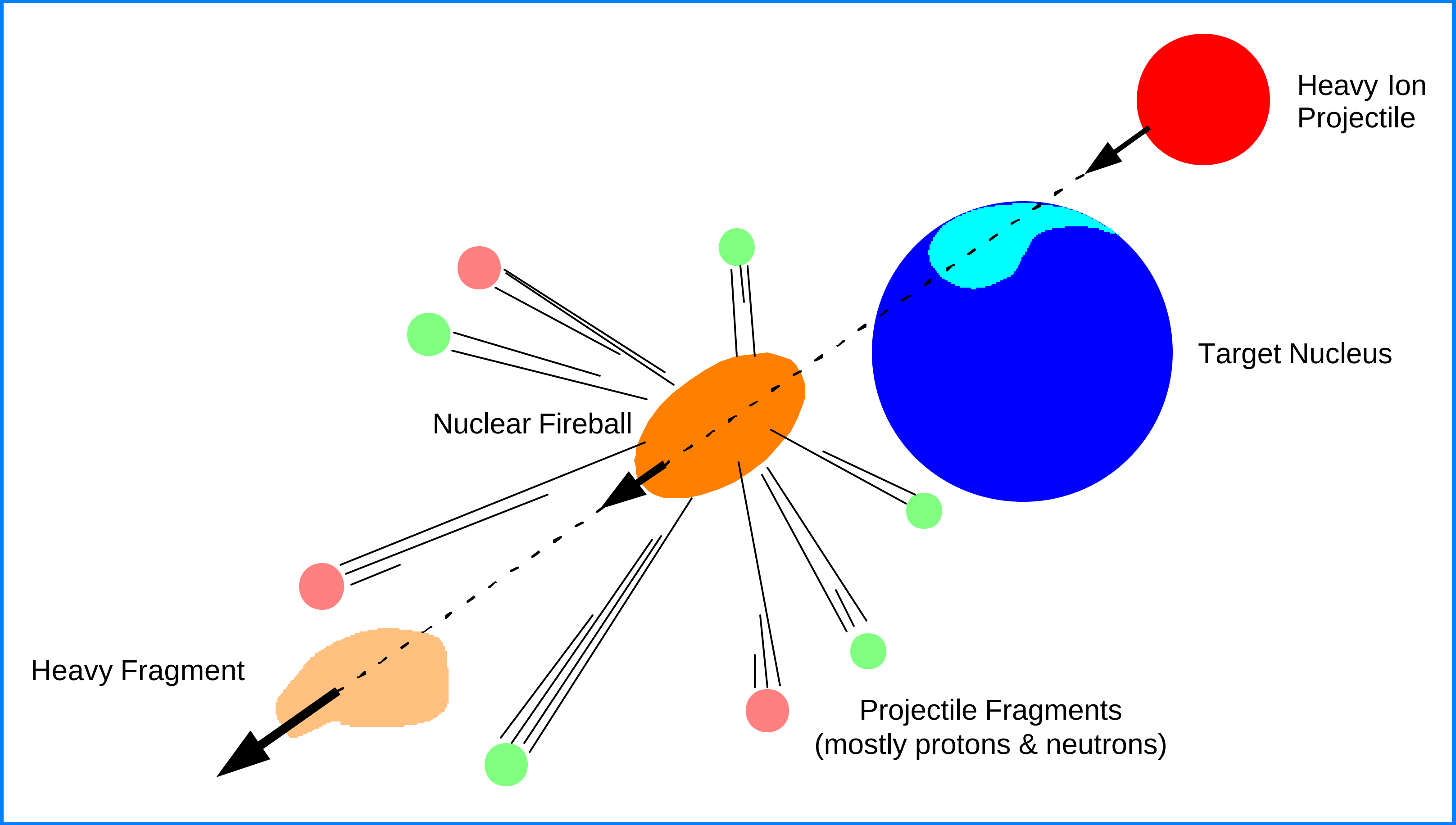
Types of Nuclear Interaction



Heavy Ion Projectile Fragmentation



BEAMS: Benchmark Evaluations and Analysis of Materials for Shielding

Objective: Provide Heavy-Ion Accelerator Data to validate the Radiation Transport Codes currently under development.

- Conduct Set of Heavy-Ion Thick Target Benchmark Measurements
    - 0.5 to >30 g/cm^2
    - High Density Polyethylene (HDPE), Aluminum, Copper
- Compare Benchmark Measurements with Results from Model Calculations and with Results from other Instruments
- Design and Fabricate Set of “Standard” Thick Target Shields: HDPE, Al, Cu; also Graphite, Tissue Equivalent Plastic, Water
- Make Benchmark Measurements of Neutron- and Proton-Induced Target Fragmentation

BEAMS/MMARSS Approach

- Use <u>same</u> instruments for transport code validation as are used aboard spacecraft for crew dosimetry (presumably same instruments that will be used on interplanetary spacecraft).
- Measure <u>same</u> dosimetric quantities (Dose, Dose Equivalent, LET/y spectra) measured for crew dosimetry.
- Make measurements using Tissue Equivalent detectors
- Carry out measurements in such a way that they can be easily and accurately modeled.

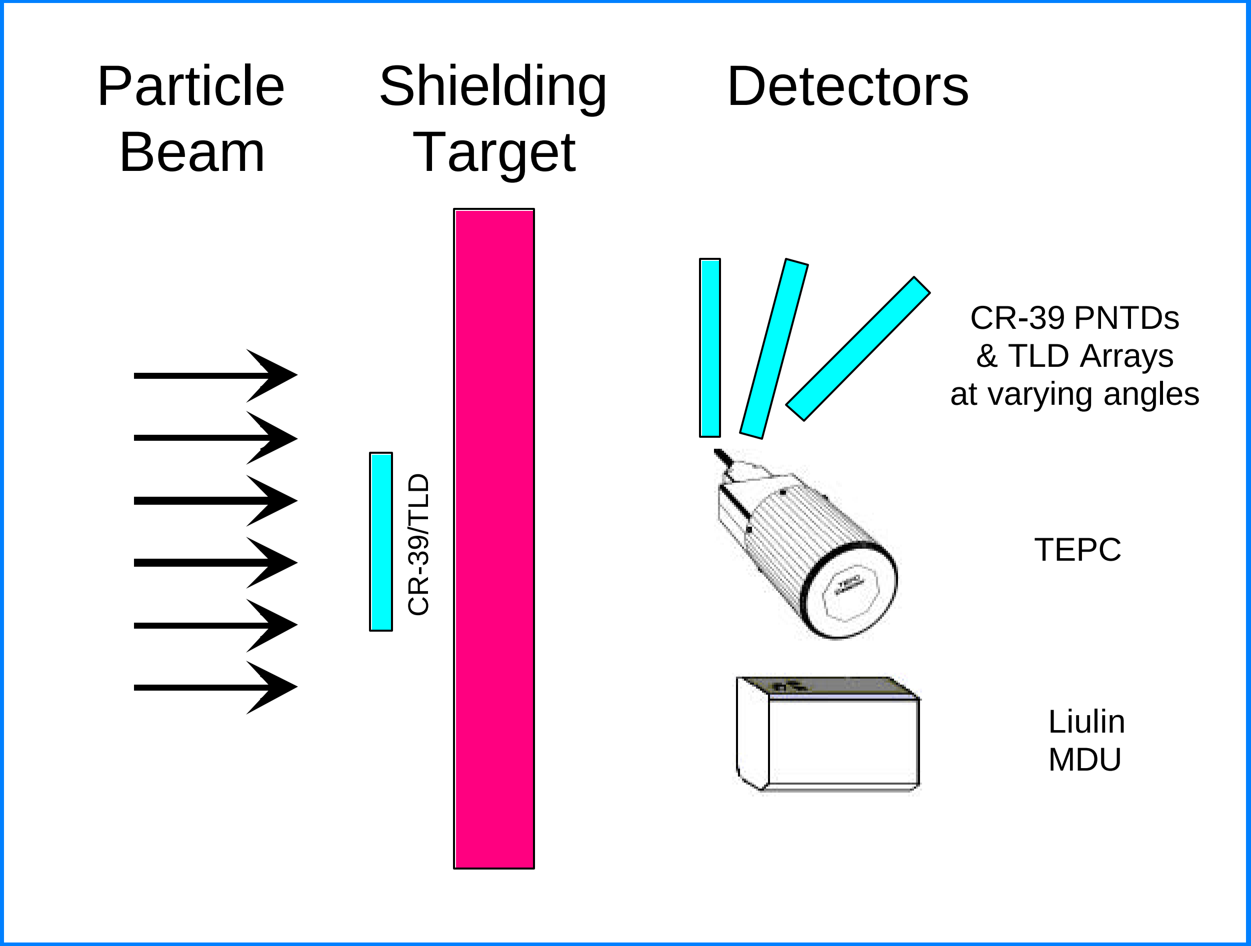
Accelerator Facilities

- NASA Space Radiation Laboratory (NSRL) at Brookhaven
    - Protons through Au (no Noble Gases)
    - 100 MeV/nucleon – 3 GeV/nucleon
- HIMAC at National Institute of Radiological Sciences, Chiba
    - He through Fe
    - 100 – 800 MeV/nucleon
- Loma Linda University Medical Center
    - 55 – 250 MeV Protons
    - Solar Particle simulation
- Los Alamos Neutron Science Center (LANSCE)
    - ≤800 MeV neutrons
    - 800 MeV protons

Detectors/Dosimeters

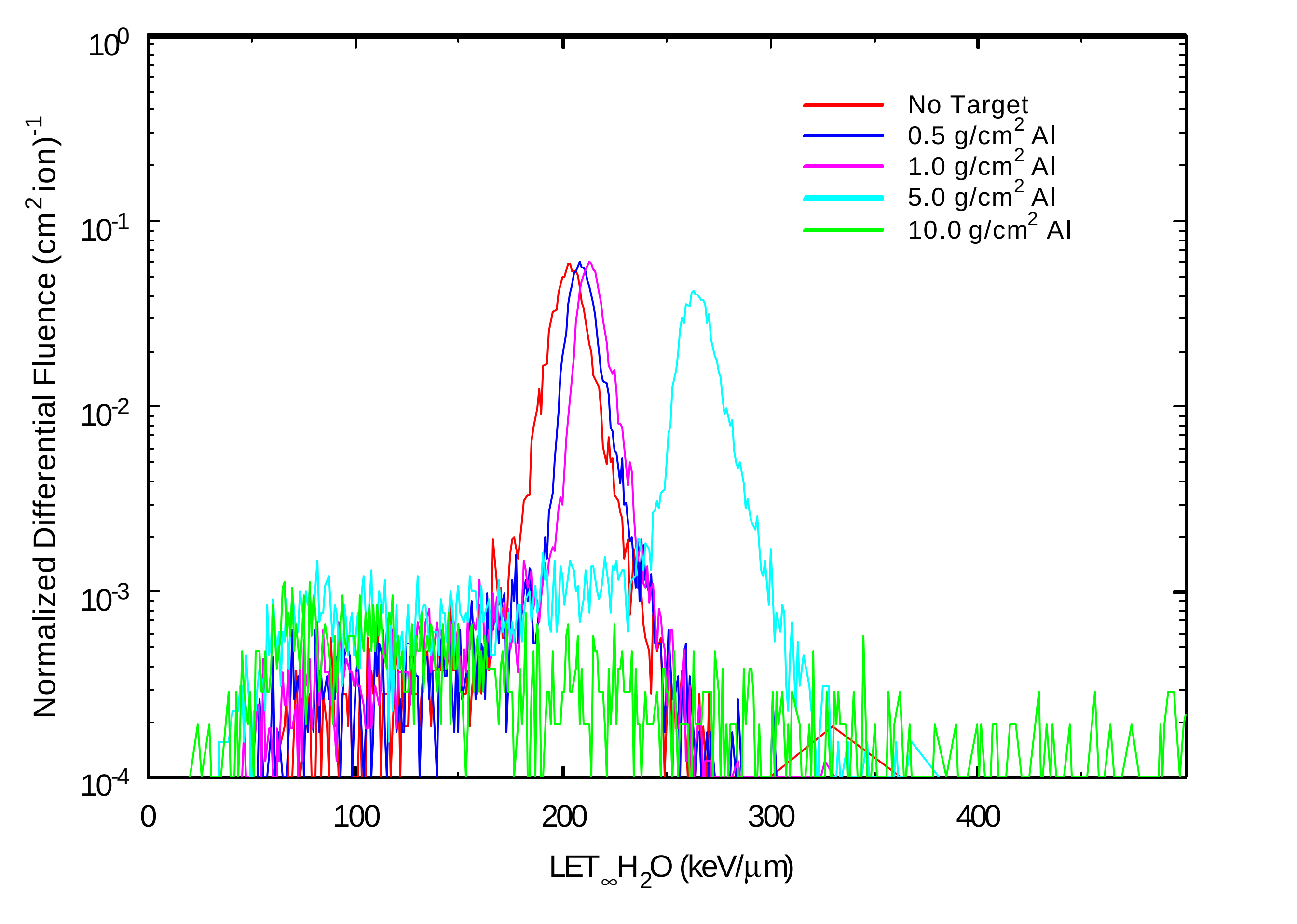
- CR-39 Plastic Nuclear Track Detector (PNTD) *–E. Benton, N. Yasuda*
    - $LET_{\infty}H_2O \geq 5$ keV/μm
    - LET Spectrum, Dose, Dose Equivalent
- Thermoluminescent Detector (TLD) *–E. Benton, A. Frank*
    - Total Absorbed Dose (high-LET with reduced efficiency)
    - Pille Portable TLD System (now in use on ISS) *-KFKI Budapest Hungary*
- Tissue Equivalent Proportional Counter (TEPC) *–B. Gersey*
    - Lineal Energy (y) Spectrum, Dose, Dose Equivalent
    - 0.5 to 1000 keV/μm
- Liulin-4 MDU Portable Si Spectrometer *–Y. Uchihori, E. Benton*
    - LET Spectrum, Dose, Dose Equivalent
    - 0.5 to 40 keV/μm

Heavy Ion Accelerator-based Testing



Differential LET Fluence Spectra measured in CR-39 PNTD

422.6 MeV/n ^{56}Fe at HIMAC, 6061 Aluminum Targets



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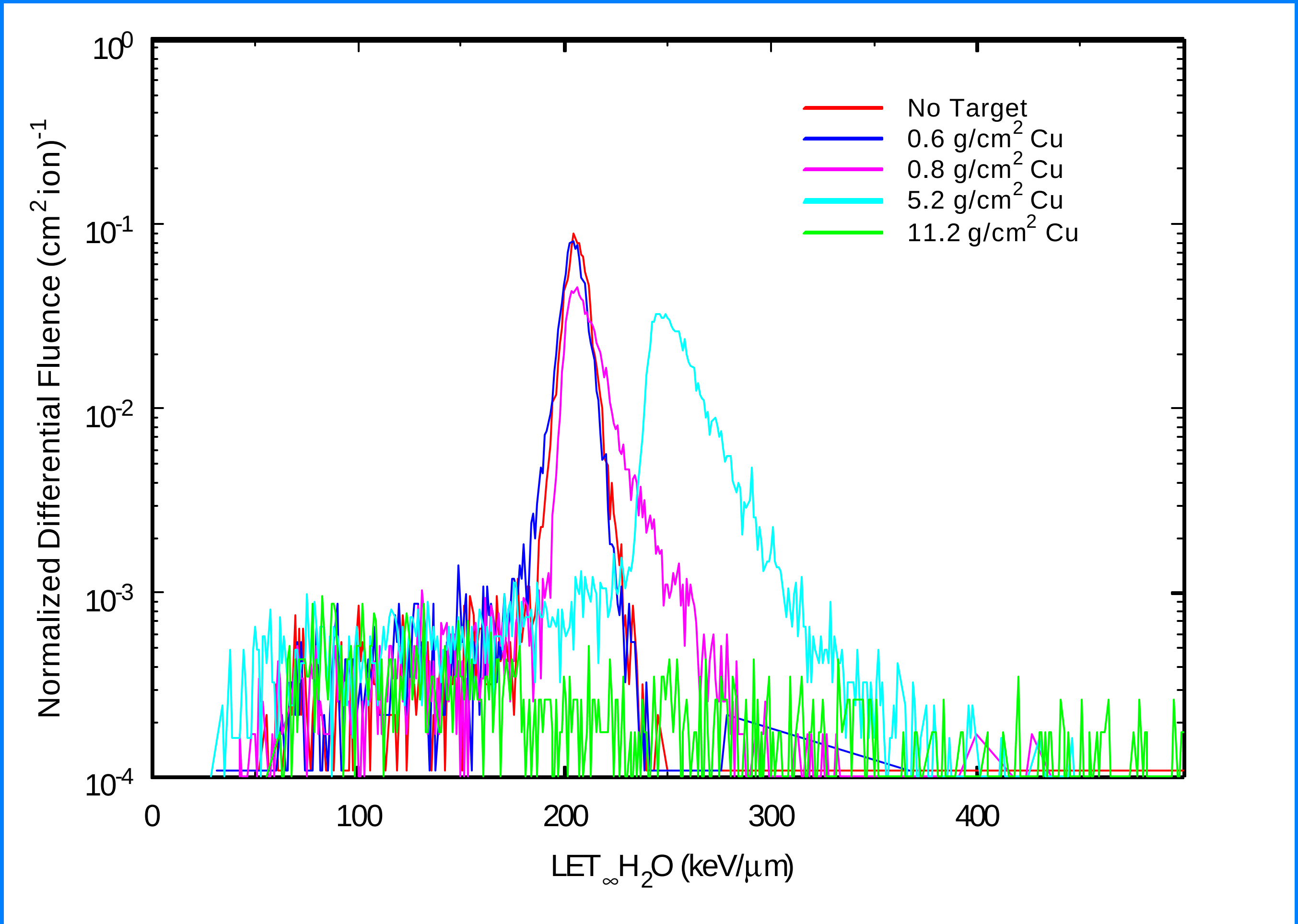
Differential LET Fluence Spectra measured in CR-39 PNTD

422.6 MeV/n ^{56}Fe at HIMAC, Copper Targets



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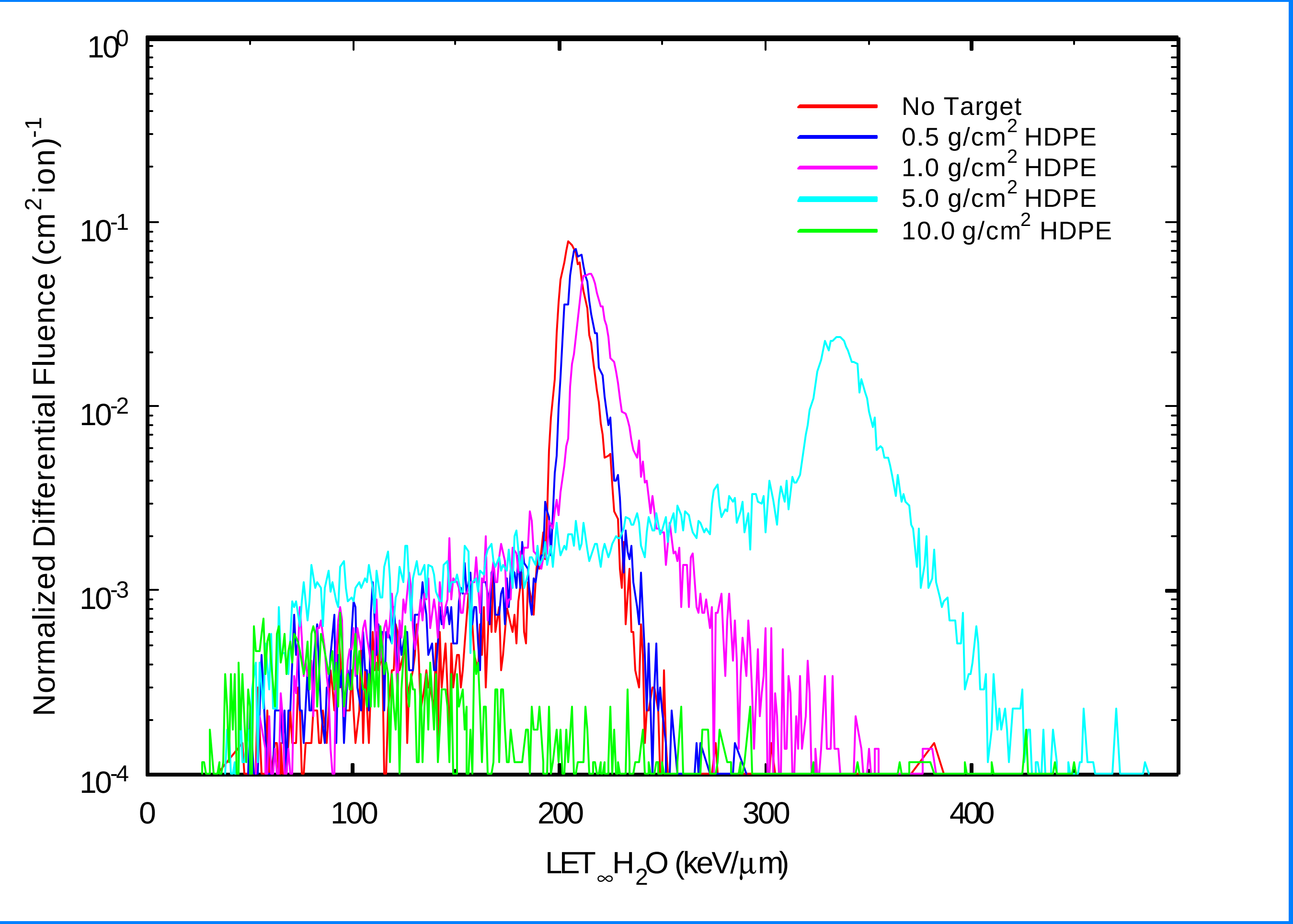
Differential LET Fluence Spectra measured in CR-39 PNTD

422.6 MeV/n ^{56}Fe at HIMAC, High Density Polyethylene Targets



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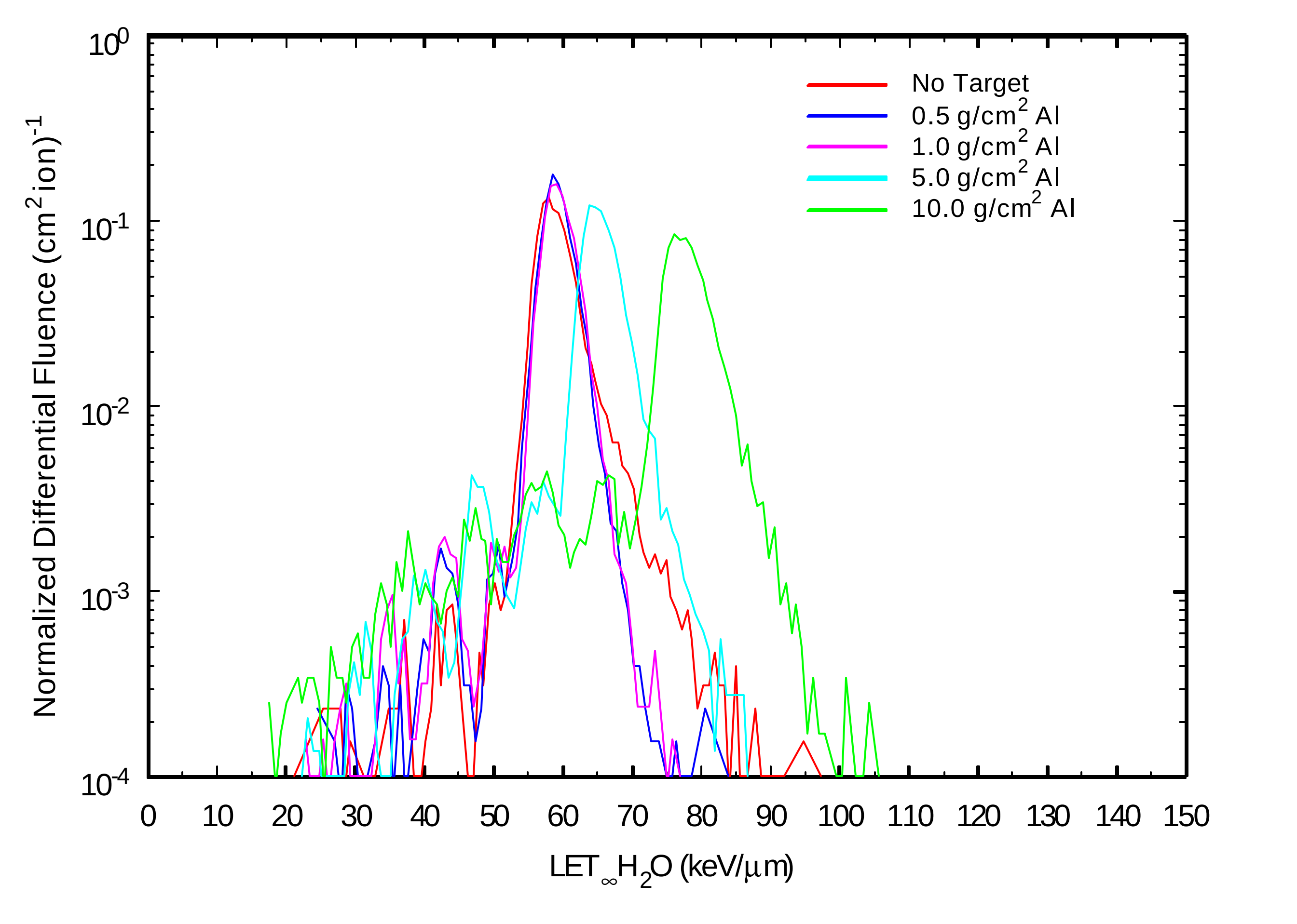
Differential LET Fluence Spectra measured in CR-39 PNTD

446.6 MeV/n ^{28}Si at HIMAC, 6061 Aluminum Targets



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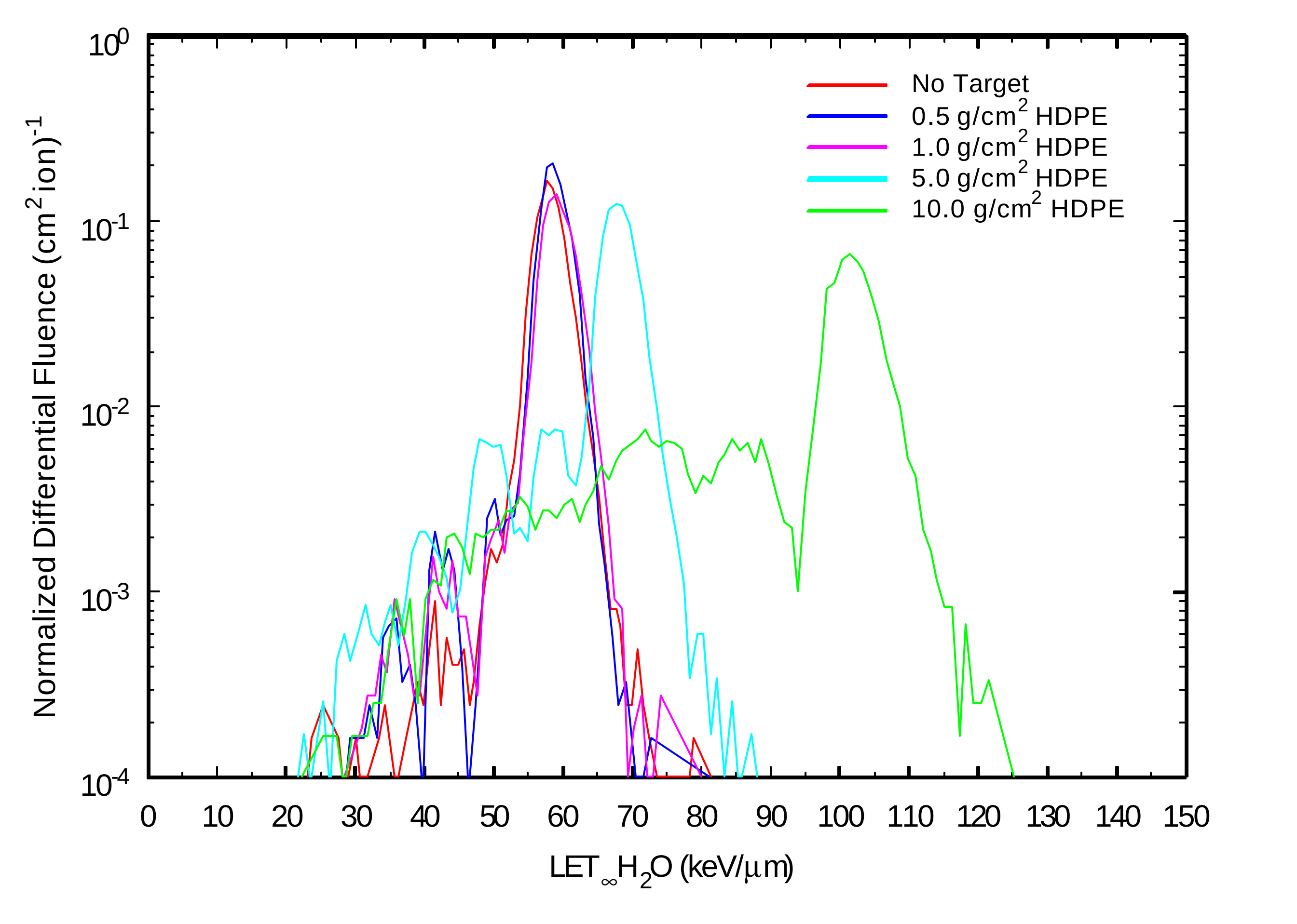

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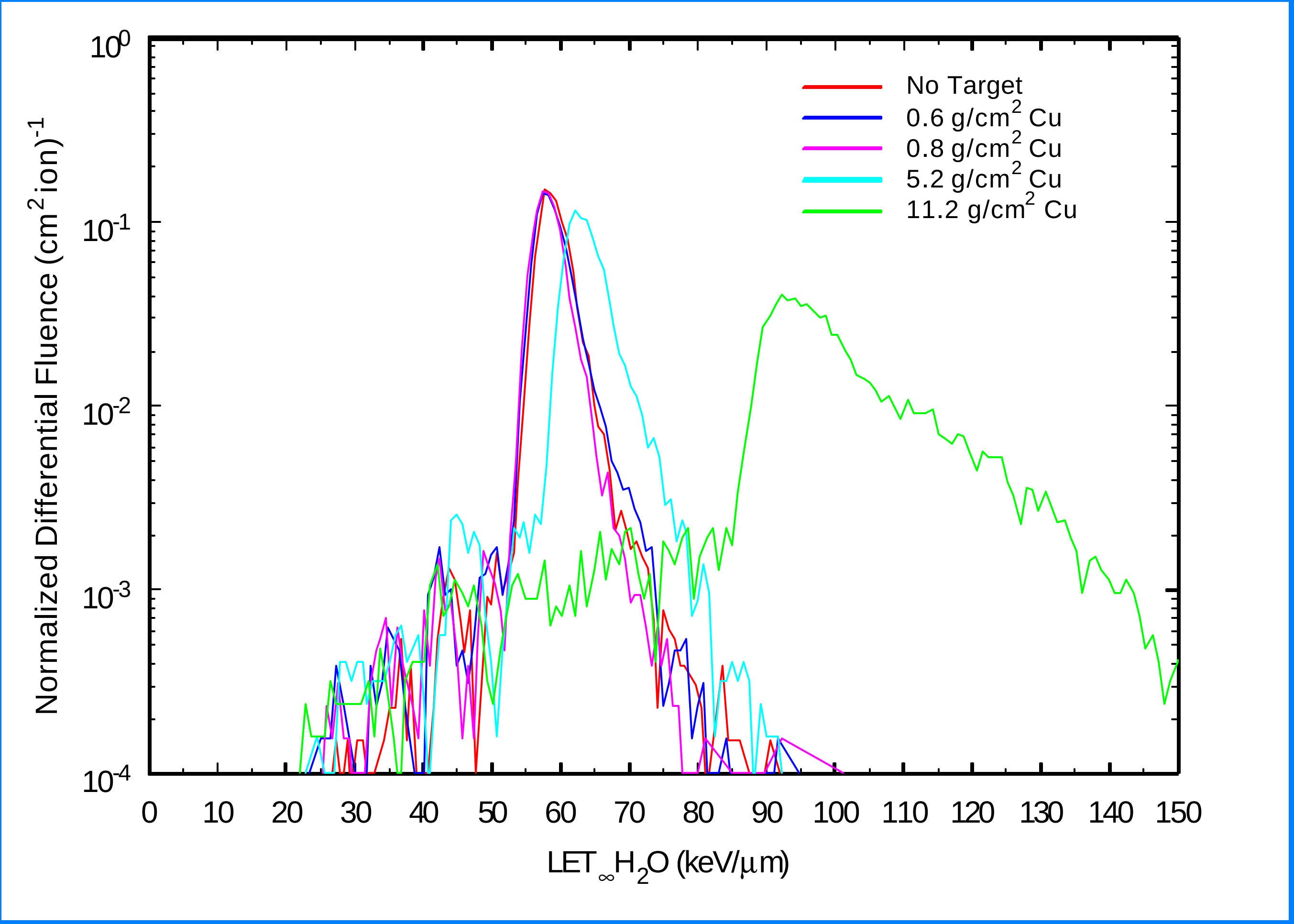
Differential LET Fluence Spectra measured in CR-39 PNTD

446.6 MeV/n ^{28}Si at HIMAC, Copper Targets



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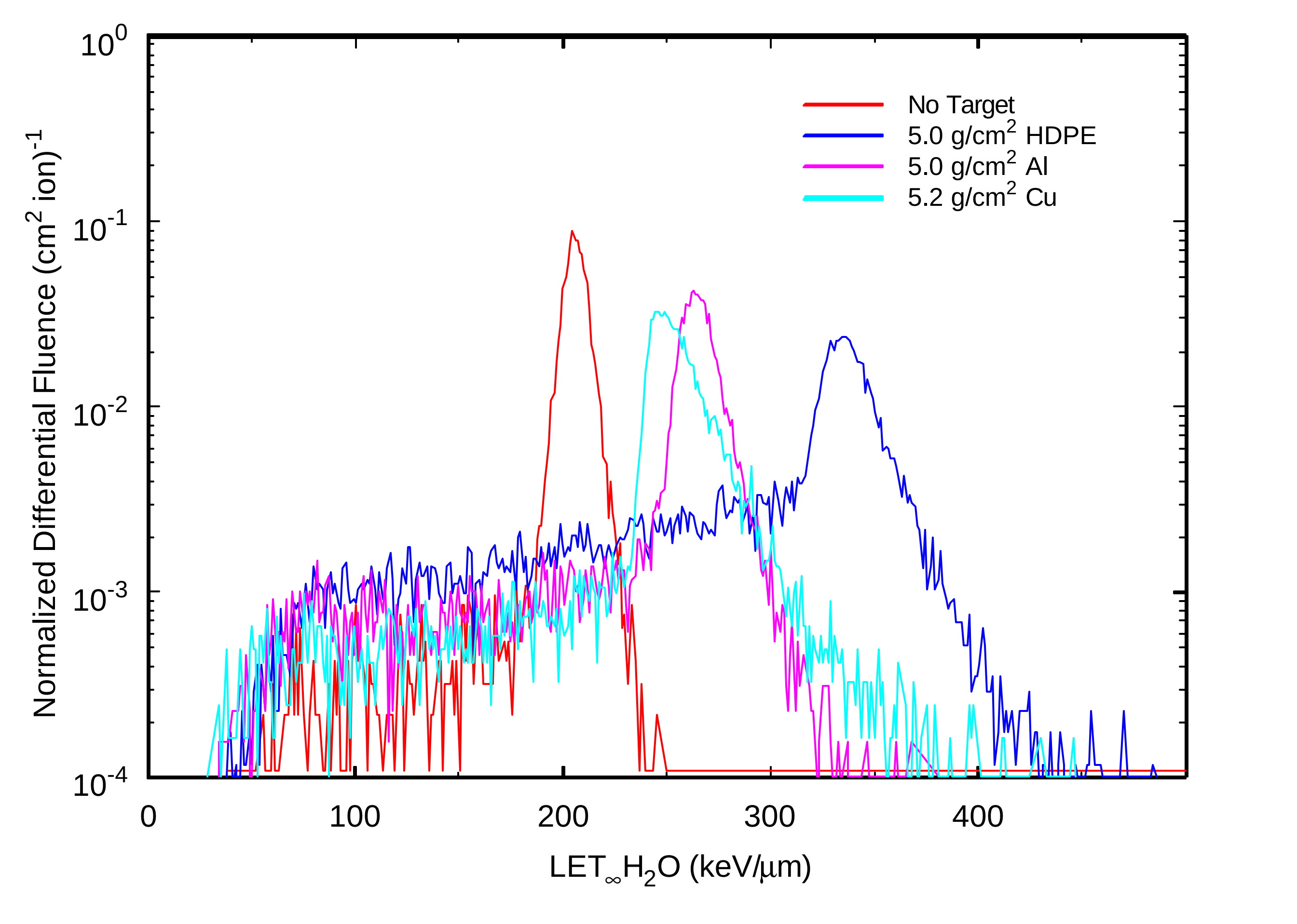
Differential LET Fluence Spectra measured in CR-39 PNTD

422.6 MeV/n ^{56}Fe at HIMAC, ~5 g/cm^2 Targets



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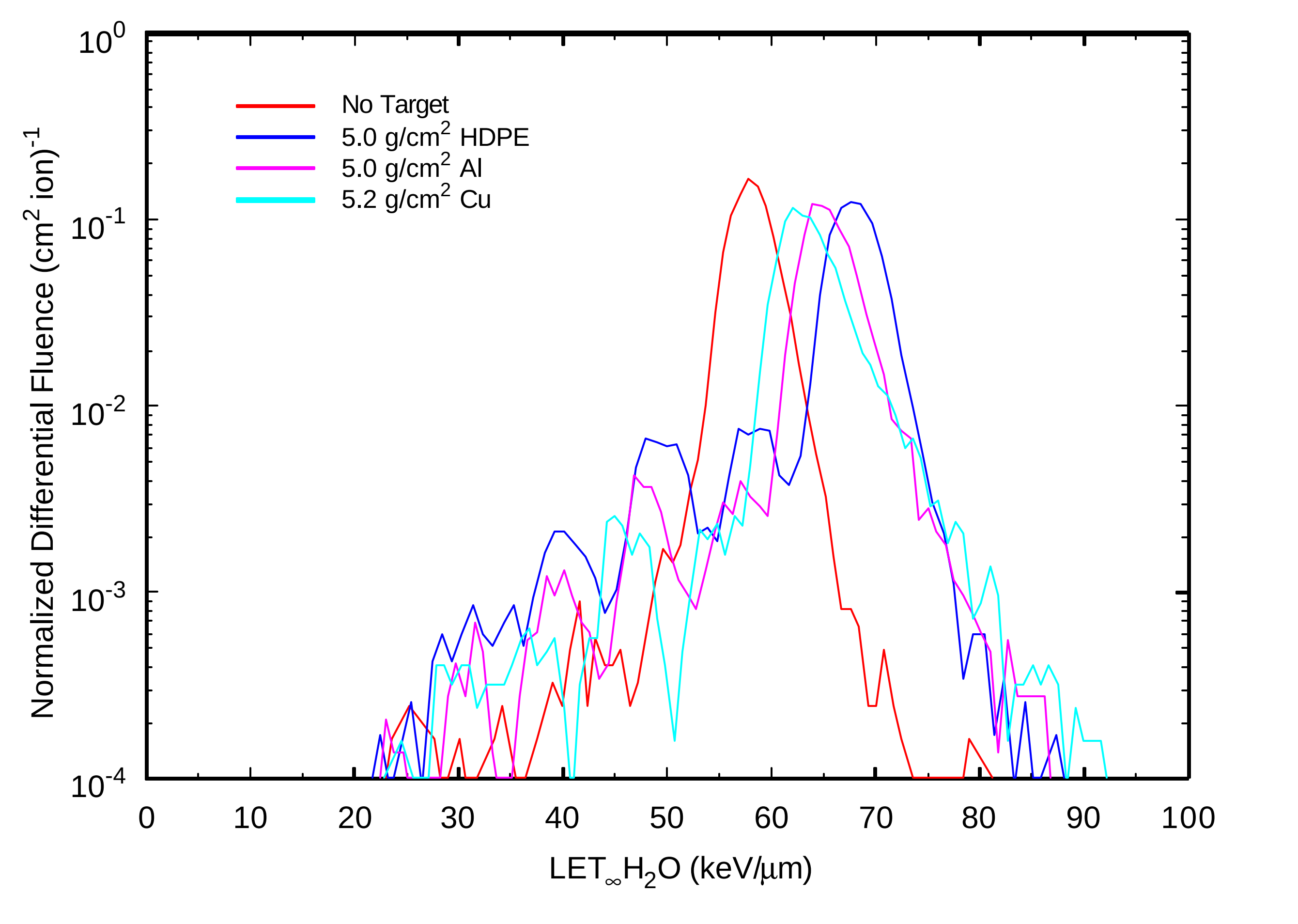

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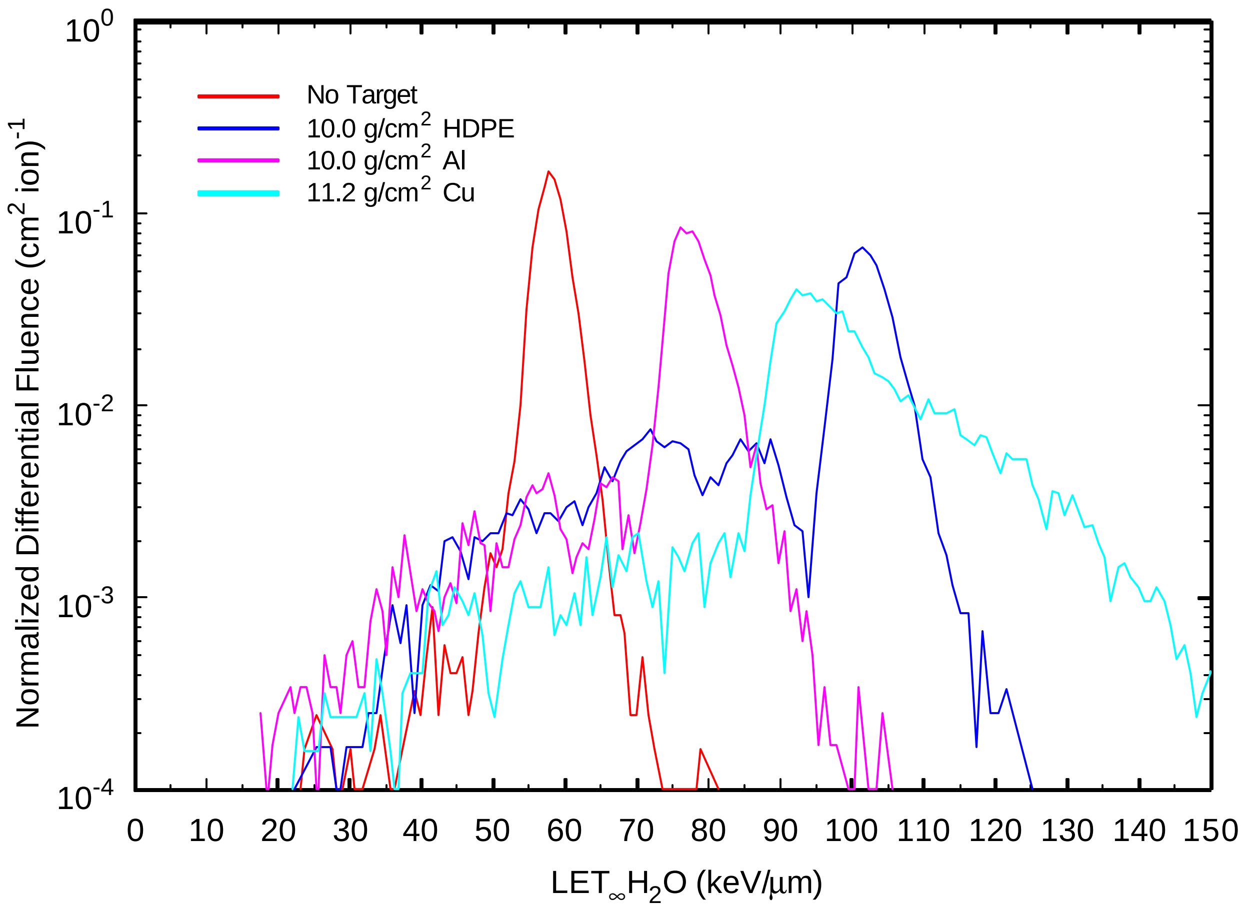
Differential LET Fluence Spectra measured in CR-39 PNTD

446.6 MeV/n ^{28}Si at HIMAC, ~10 g/cm^2 Targets



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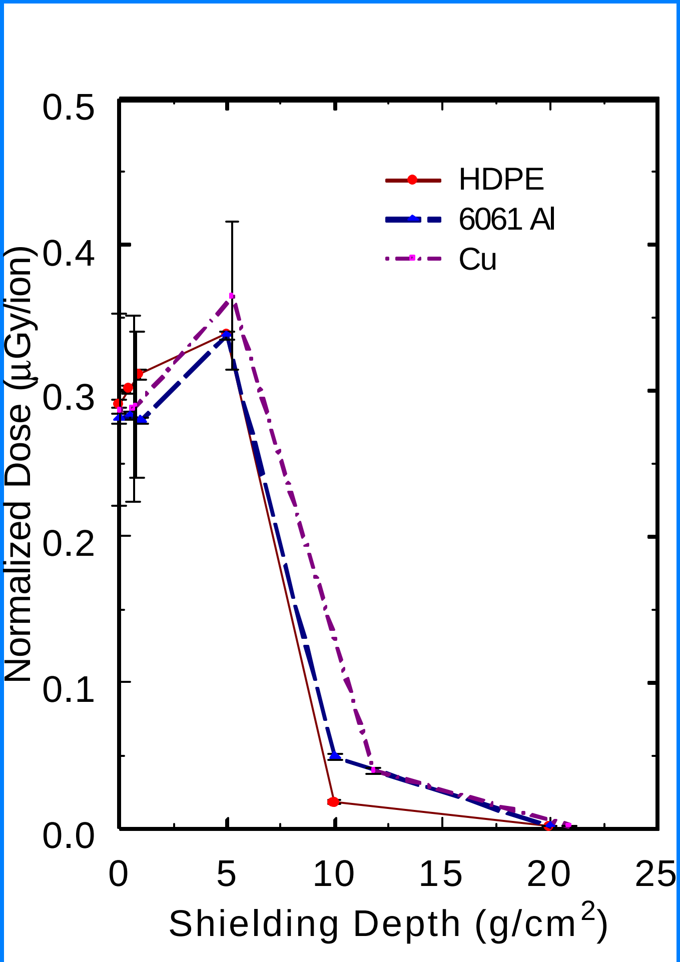
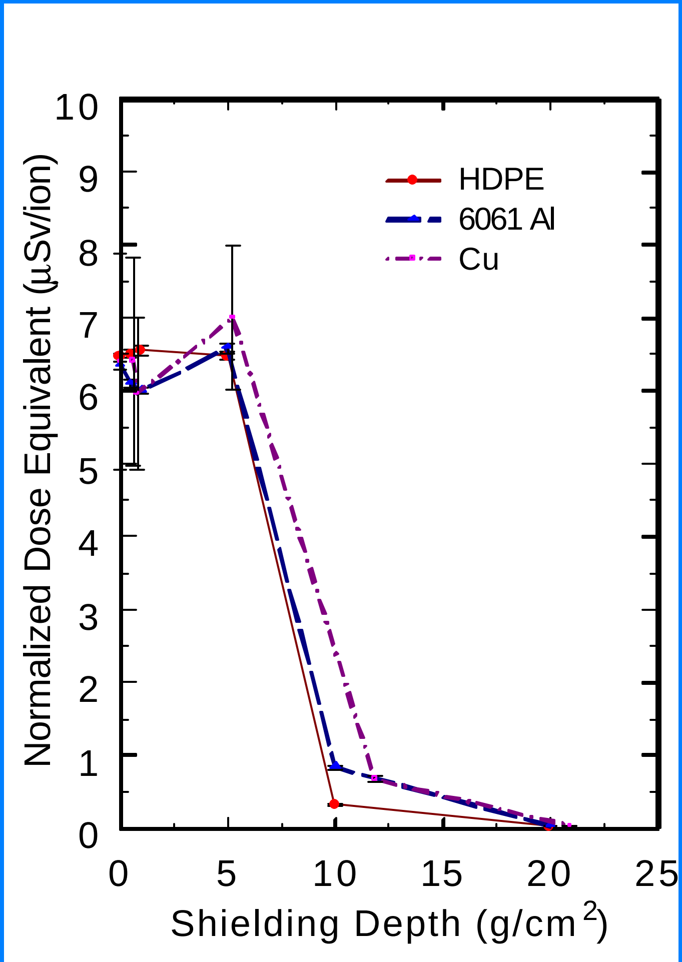
Dose & Dose Equivalent as Functions of Depth

422.6 MeV/n ^{56}Fe in HDPE, Al and Cu Targets





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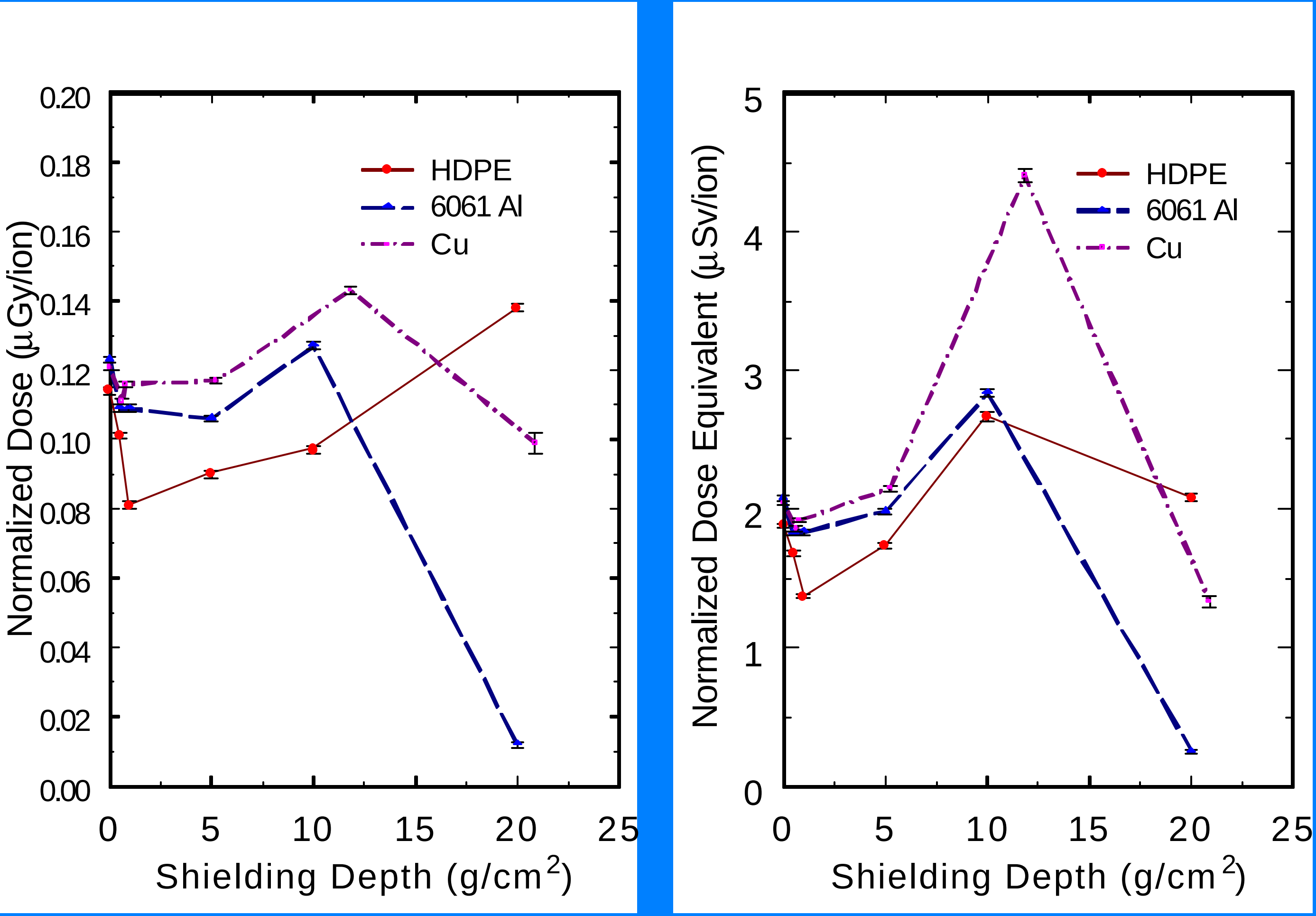

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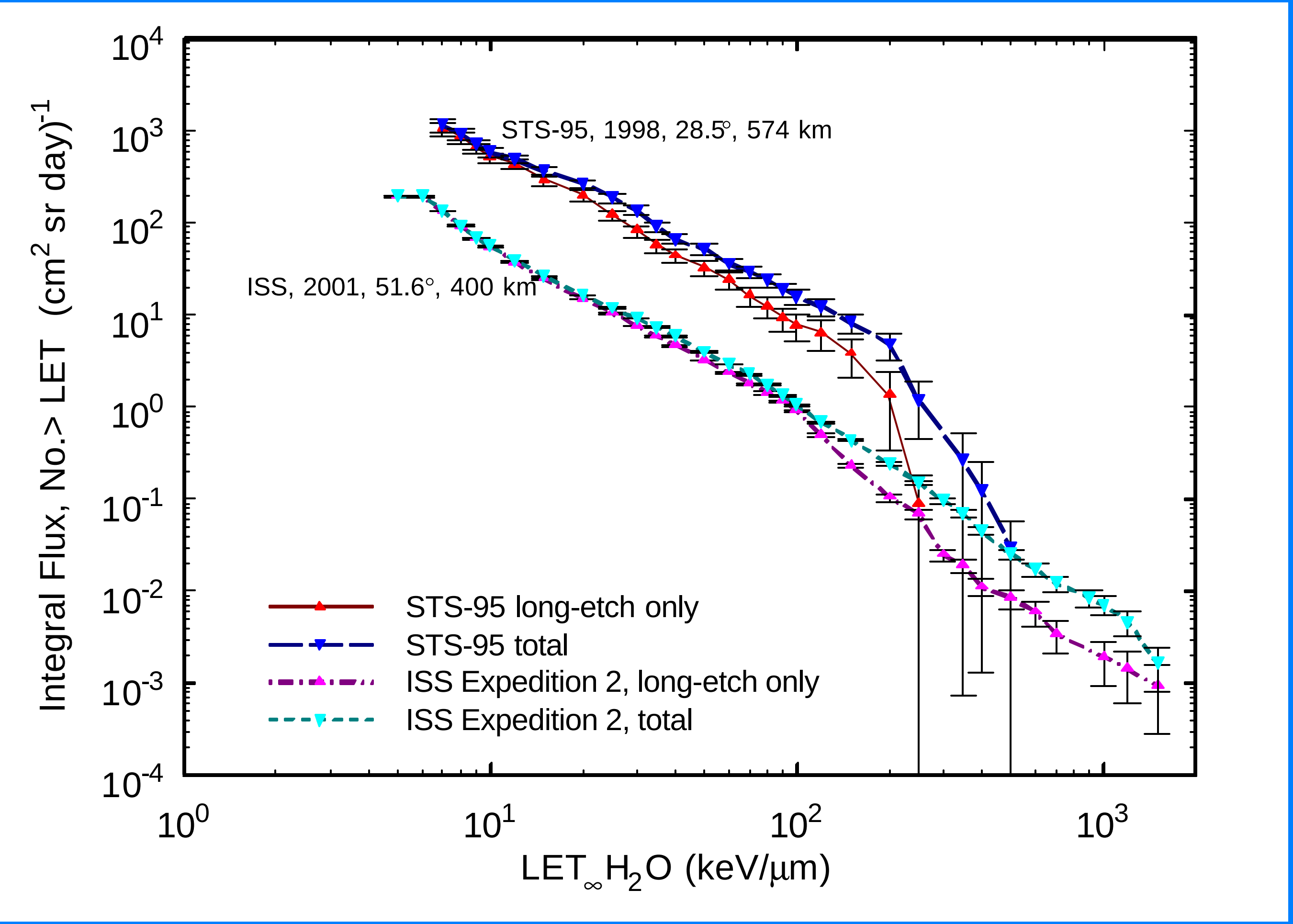
Importance of Neutrons when Developing Shielding Materials

- Neutrons interact with matter (tissue) by means of elastic scattering with hydrogen
- High-Energy Neutrons (and Protons) interact with matter by means of non-elastic target fragmentation with heavy nuclei (C and O in body, Si in electronics)

The best way to shield a spacecraft from neutrons is to not produce them in the first place –Larry Townsend

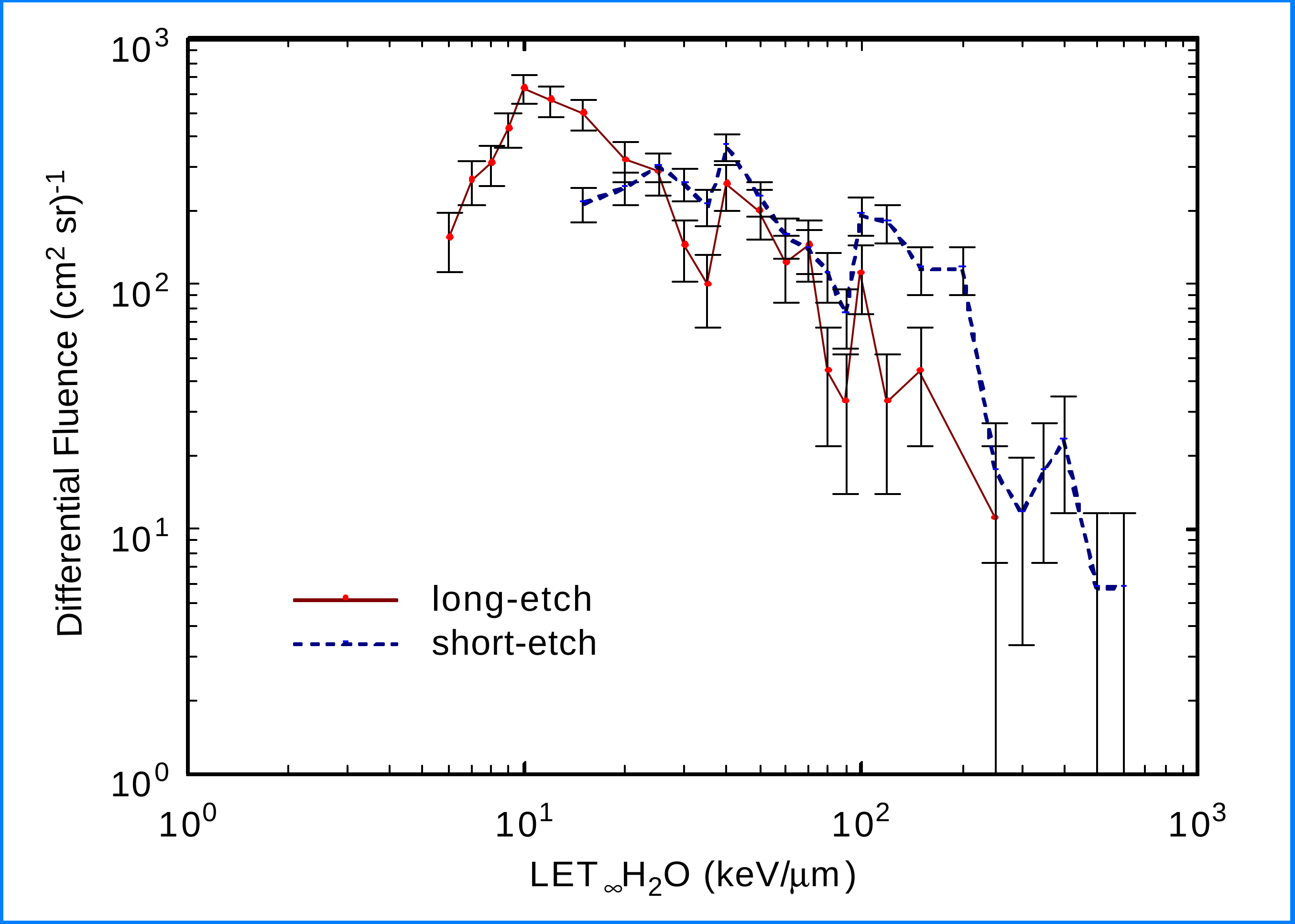
Integral LET Flux Spectra measured in CR-39 PNTD

Dependence of neutron- and proton-induced target fragmentation contribution on orbital inclination and altitude in LEO



Differential LET Fluence Spectra measured in CR-39 PNTD

173 MeV protons, 90°, Svedberg Laboratory, Uppsala



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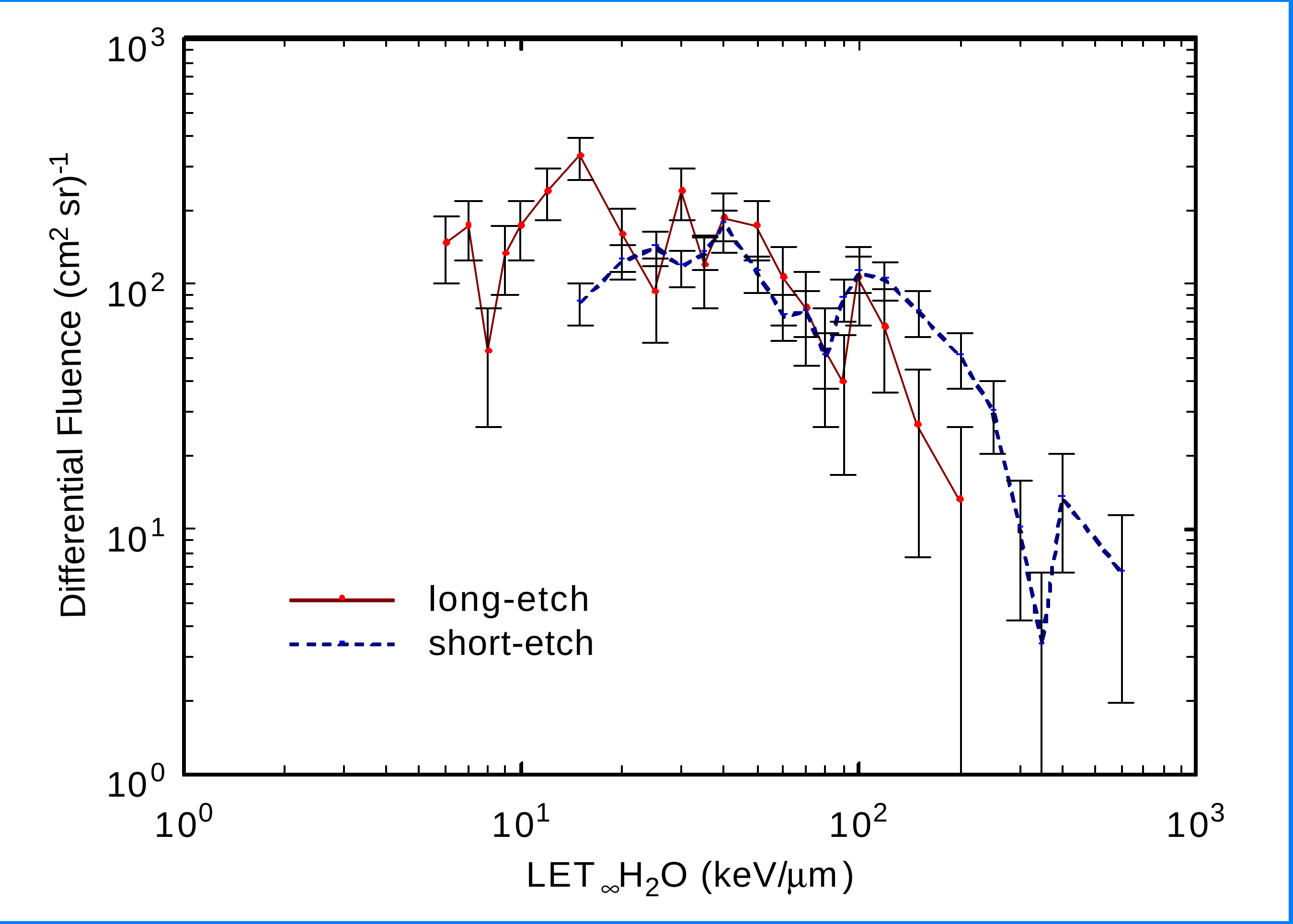
Differential LET Fluence Spectra measured in CR-39 PNTD

≤180 MeV neutrons, 90°, Svedberg Laboratory, Uppsala



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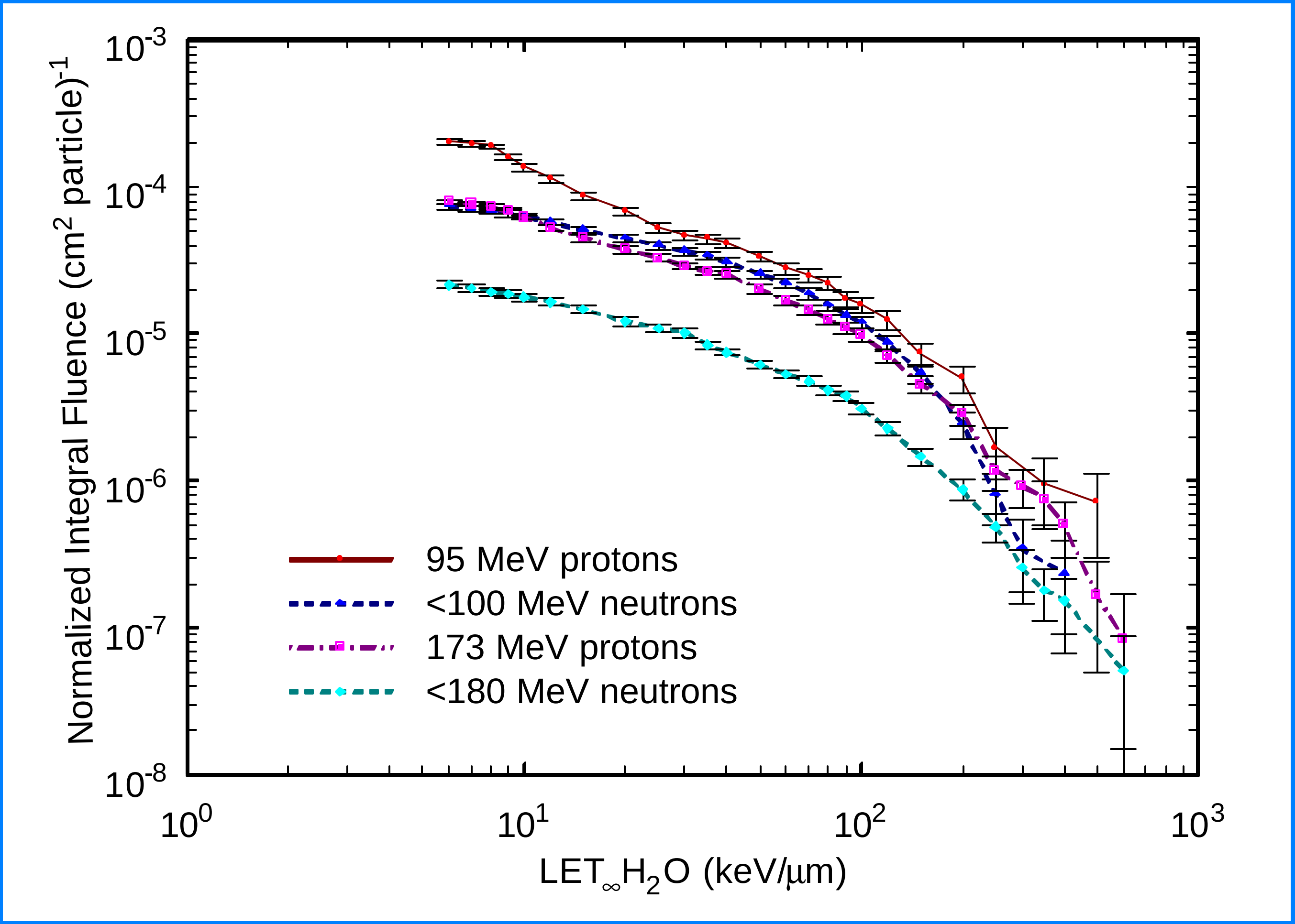
Integral LET Fluence Spectra measured in CR-39 PNTD

Protons and Neutrons Exposures, 90°, Svedberg Laboratory, Uppsala



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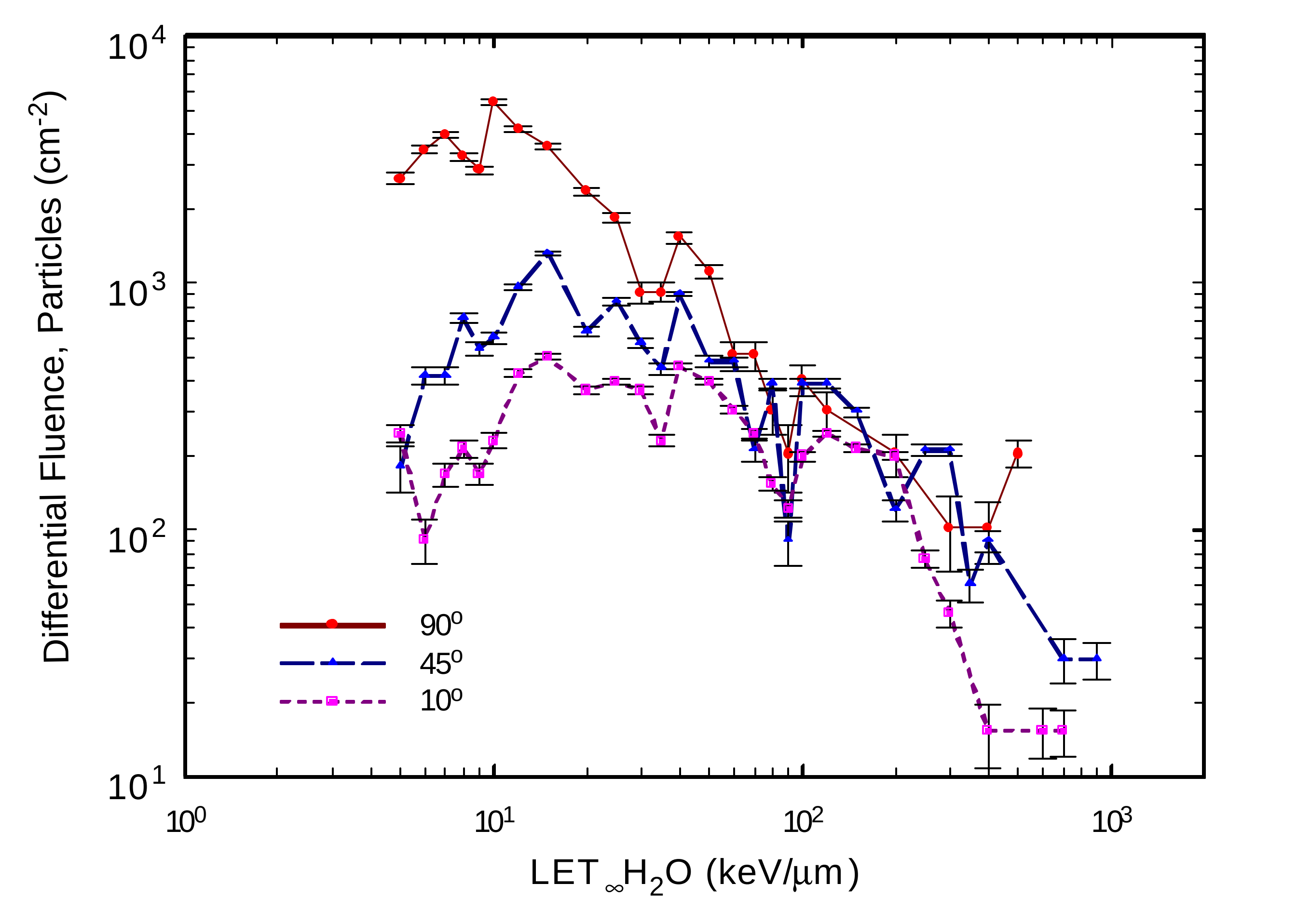
Differential LET Fluence Spectra measured in CR-39 PNTD

175 MeV Protons, 3 Incident Angles, Loma Linda



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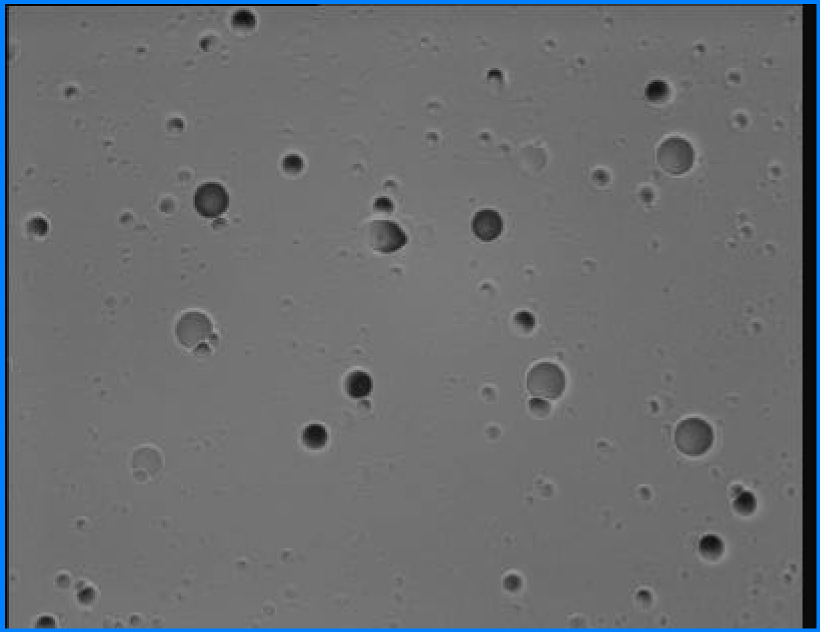
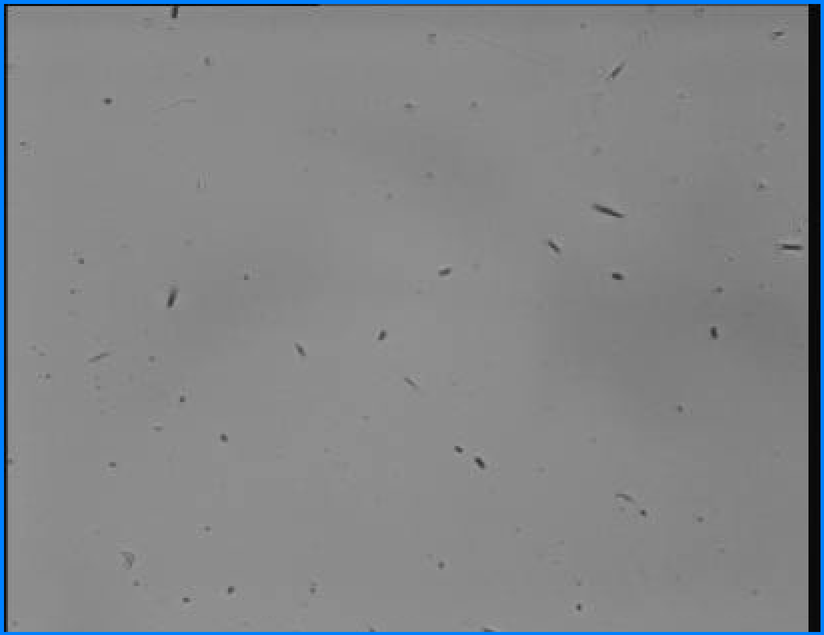
CR-39 PNTD Exposed to 230 MeV Protons at LLUMC



Protons & α-particles

B = 8.0 μm, 500×



Short-Range Heavy Recoils

B = 0.5 μm, 500×

Low mean atomic number (Z) materials tend to provide the best radiation shielding.

- Materials with low mean atomic mass mean more nuclei in the path of the incident cosmic ray (short mean path length) helping to break up heavy charged particles.
- Lighter target nuclei contain fewer neutrons (H contains none at all) so fewer secondary neutrons are created.
- Low Z nuclei are less effective in creating electrons and positrons by pair production and x-rays by Bremsstrahlung.
- Some nuclei, notably C and O, tend to emit α-particles instead of neutrons when hit by incident cosmic rays.
- Polyethylene (CH_2, 14% Hydrogen by mass) is considered the standard against which all new shielding materials are compared.

MMARSS: Multifunctional Materials Analysis of Radiation Shielding for Spacecraft

Objective: Characterize the Radiation Shielding Properties of Novel, Multifunctional Materials via Heavy-Ion Accelerator Testing.

- Select and develop prototype Multifunctional Spacecraft Materials
- Test shielding effectiveness via particle accelerator-based exposures
- Model shielding effectiveness using space radiation transport codes (HZETRN, HETC, FLUKA, MCNPX)
- Create Shielding Materials Database

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"Revolutionary" Shielding Concepts/Materials being considered by NASA

- Active Shielding
  - Electrostatic
  - Magnetic
- Hydrogen-filled Carbon Nanotubes (6-20% H by mass, dual use as shielding and structure/H storage).
- Metal Hydrides (7-18% H by mass, use for H storage in Fuel Cells).
- Palladium Alloys for H storage (4% H reported)
- Liquid/Solid Hydrogen

None of these concepts/materials is likely to be practical for some time, if ever (low NASA Technical Readiness Levels).

Approach of MMARSS Project

The MMARSS Project is taking a pragmatic approach in its choice of shielding materials for development and testing.

- Materials familiar to the Aerospace Industry (what do people make spacecraft out of and why?)
- Make maximum use of what is already available
- Realistic, not “revolutionary” gains in shielding performance
- Emphasize “multifunctional” nature of materials
- Don’t be afraid to use “Dirty Hands” methods (i.e. fabricating own material samples)

Shielding Materials for MMARSS Project

- Composites (perhaps with high H content in Epoxy resin)
  - Carbon, Polyethylene, Aramid (Kevlar)
- Thermoplastics and Structural Polymers with high H content
- Multilayered (honeycomb) materials with polyethylene or other high H content fillers
- ^{10}B or ^{6}Li doped polymers or resins (to shield out thermal neutrons)
- Materials with thin layers of Cd or Ta to shield out thermal neutrons
- Simulated Martian and Lunar Regolith w/wo Epoxy Binder
- Consumables (fuel, water)
- Looking for other "good ideas"

Conclusions

- Both BEAMS and MMARSS Projects are underway
  - Loma Linda SPE Simulation: May 1-2
  - HIMAC Beamtime in Jan/Feb, June 4-19 (C, O, Ar, and Kr)
  - NSRL Beamtime in March (Si and Fe) and Sept. (H and O)
  - Busy Analyzing TEPC and CR-39 data
- Working in Close Collaboration with Measurements Consortium (Miller et al.)
- Looking Forward to Participation of Transport Code Community in Modeling BEAMS Experiments
- Hope to Extend BEAMS/MMARSS into the actual GCR Environment aboard the Deep Space Test Bed.